Observation of χ_{c2} Production in B-meson Decay

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We report the first observation of χ_{c2} production in B-meson decays. We find an inclusive $B \to \chi_{c2}X$ branching fraction of $(1.80^{+0.23}_{-0.28} \pm 0.26) \times 10^{-3}$. The data set, collected with the Belle detector at the KEKB e^+e^- collider, consists of 31.9 million $B\bar{B}$ events. We also present branching fractions and momentum spectra for both χ_{c1} and χ_{c2} production.

Although the theory for weak decays of b quarks is formulated in terms of quark processes, experiments are done with B hadrons. The application of quantities calculated at the quark level to the physically realizable hadrons usually requires theoretical assumptions and approximations. One widely used approximation is "factorization," where it is assumed that the participating quarks form hadrons with no subsequent transfer of quantum numbers between them [1]. Since this assumption is widely used, it is important that the range of its validity is carefully tested.

In the factorization limit, decays of the type $B \to \chi_{c0}X$ and $\chi_{c2}X$ are not allowed by angular momentum and vector-current conservation [2]. These decays can occur if there is a (factorization-violating) exchange of soft gluons between the quark pairs prior to hadron formation. Belle has recently reported the observation of the decay $B^- \to \chi_{c0}K^-$ with a decay branching fraction that is comparable to that for the factorization-allowed decay $B^- \to J/\psi K^-$ [3]. The CLEO collaboration has published a 95% CL upper limit on the inclusive decay $B \to \chi_{c2}X$ of 2.0×10^{-3} [4].

In this paper we report evidence for the inclusive decay $B \to \chi_{c2}X$ from an analysis of 31.9 million $B\bar{B}$ events produced in a 29.4 fb^{-1} data sample taken at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric e^+e^- collider. An additional 3.0 fb^{-1} sample taken at a center-of-mass energy 60 MeV below the $\Upsilon(4S)$ is

used to study backgrounds from non-resonant (continuum) processes.

The Belle detector consists of a three-layer silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Čerenkov counters (ACC), time-of-flight scintillation counters (TOF), a CsI(Tl) crystal electromagnetic calorimeter (ECL), a 1.5 T superconducting solenoid coil and an instrumented iron-flux return for muon and K_L detection (KLM). The detector is described in detail elsewhere [5].

Events with candidate B mesons are selected by first applying general hadronic event criteria. These include the requirement of at least three charged tracks, an event vertex consistent with the interaction point, reconstructed center-of-mass (CM) energy greater than $0.2\sqrt{s}$, a longitudinal component of reconstructed CM momentum less than $0.5\sqrt{s}/c$, and a total ECL energy between $0.1\sqrt{s}$ and $0.8\sqrt{s}$ with at least two energy clusters. To suppress continuum backgrounds we also require the ratio of the second to zeroth Fox-Wolfram moments to be less than 0.5 [6].

We reconstruct χ_{c1} and χ_{c2} via the decays to $J/\psi\gamma$, $J/\psi \to l^+l^-$. Both leptons are required to be loosely identified as leptons. Electrons are identified using a combination of drift chamber dE/dx measurements, aerogel response, and electromagnetic shower position, shape and energy. Muons are identified with KLM hit positions and penetration depth. In order to recover dielectron events where one or both electrons have radiated a photon (final state radiation or bremsstrahlung), we include the four-momentum of every photon detected within 0.05 radians of the original e^+ or e^- direction in the invariant mass calculation. The $J/\psi \to \mu^+\mu^- (e^+e^-)$ candidate invariant mass is required to be between $-25(-40)$ MeV/c^2 and $+25$ MeV/c^2 of the known J/ψ mass, with an expected resolution of 9.6(10.8) MeV/c^2 for dimuon(dielectron) J/ψ's. The larger range for dielectron candidates is to include candidates that fall in the radiative tail, even after the photon correction.

To reduce combinatoric background, we veto gamma candidates that form a good π^0 candidate with any other photon candidate of energy greater than 60 MeV in the event. A good candidate π^0 is defined by a χ^2 of less than 10 after a mass-constrained kinematic fit. We then make a histogram of the mass difference between the χ_c and the J/ψ candidates; this nearly eliminates the effect of the J/ψ measurement error. The error on the mass difference is dominated by the photon energy resolution. The momentum of the χ_c candidate in the CM reference frame is required to be less than 1.7 GeV/c (the kinematic limit for a χ_c coming from a B meson); this requirement was not used in the determination of the χ_c momentum spectra.

In Fig. 1 a clear χ_{c2} peak can be seen next to a larger χ_{c1} peak. In order to determine the yield we fit the distribution to two Crystal Ball line shapes [7] and a third-
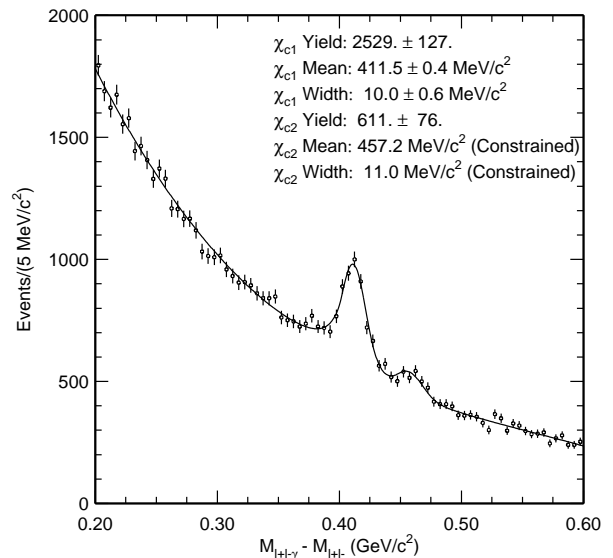

FIG. 1: The $\chi_c - J/\psi$ mass difference distribution for candidate events. The widths reported correspond to the "width" parameter of the Crystal Ball function [7].

order Chebyshev polynomial for the background. The Crystal Ball function allows for a "tail" in the line shape that is due to photon shower leakage in the ECL.

In this fit (the "standard" fit), the signal line shapes (i.e. the widths, means, and tail parameters) are allowed to float with the following constraints: the difference between the means is fixed to the known $\chi_{c1} - \chi_{c2}$ mass difference; the χ_{c2} width is fixed to 1.1 times the χ_{c1} width, to take into account the Monte Carlo expected ratio of the widths, which is consistent with a higher average χ_{c2} photon energy; and the tail parameters are fixed to be the same. The background shape is fixed by fitting to the regions outside the signal region from 0.35 to 0.50 GeV/c^2.

The signal shape was compared with predictions from an inclusive $B \to \chi_{c1}X$ and $\chi_{c2}X$ full Monte Carlo simulation. The signal widths in data are larger. In a study of $D^{*0} \to D^0\gamma$, we find that the calorimeter response for a single photon is broader in the data than in the Monte Carlo: for the $\chi_c - J/\psi$ mass difference, we expect the width to be increased by a factor of 1.3. For χ_{c1} the Monte Carlo width is 7.0 ± 0.2 MeV/c^2, the corrected width is 9.1 ± 0.3 MeV/c^2, and the measured width is 10.0 ± 0.6 MeV/c^2. We consider the variation in signal yields for various fitting scenarios in determining the systematic error due to fitting.

The background shape was checked against a full Monte Carlo simulation that included the appropriate amounts of $B\bar{B}$ and non-resonant events. The Monte Carlo and data background shapes are in good agreement and their normalizations agree within 3%.

We find a yield of 2529 ± 127 events in the χ_{c1} peak and 611 ± 76 events in the χ_{c2} peak, where the error is

statistical only.

Several sources of background production were checked. Two-photon processes produce χ_{c2} [9]. To estimate the contribution to the χ_{c2} signal from events of this type we looked at the equivalent of 560 fb^{-1} of Monte Carlo data. From this sample we estimate a background contribution of 1.9 events. We also checked the 3.0 fb^{-1} continuum data sample for χ_c production. We expect a small number of events from feed down from continuum $\psi(2S)$'s and possible direct χ_c production. From the fit we find 14.0 ± 6.4 events in the χ_{c1} region and 0.4 ± 5.7 events in the χ_{c2} region. Expected contributions of feed down from continuum $\psi(2S)$ production are 0.5 events for χ_{c1} and 0.2 events for χ_{c2} [10], and, hence, consistent with the above measurements. For the χ_{c2} case, we follow the prescription of Feldman and Cousins and find the 68.27% confidence interval for the event yield to be [0.0,6.1] [11]. We scale the continuum yields by the ratio of on- and off-resonant luminosities, corrected for the difference in continuum cross section due to the slight difference in beam energies. The scaled χ_{c1} and χ_{c2} continuum yields are subtracted from the on-resonance yields. We use the Feldman-Cousins confidence limits in determining the statistical error for χ_{c2} after the subtraction.

To convert yields to branching fractions we determine the reconstruction efficiency with a full inclusive $B \to \chi_{c1}X$ and $\chi_{c2}X$ Monte Carlo. We find the efficiencies for reconstruction to be $32.0 \pm 0.5\%$ and $33.1 \pm 0.9\%$, respectively. The χ_c momentum spectra of the Monte Carlo are similar to those measured in data. The efficiencies are uniform over the allowed χ_{c1}, χ_{c2} momentum range.

We use the 2001 Particle Data Group [8] values for daughter branching fractions $\mathcal{B}(J/\psi \to l^+l^-) = 0.118 \pm 0.002$, $\mathcal{B}(\chi_{c1} \to J/\psi\gamma) = 0.273 \pm 0.016$, and $\mathcal{B}(\chi_{c2} \to J/\psi\gamma) = 0.135 \pm 0.011$. The inclusive $B \to \chi_c X$ branching fractions are found to be: $\mathcal{B}(B \to \chi_{c1}X) = (3.63 \pm 0.22) \times 10^{-3}$, and $\mathcal{B}(B \to \chi_{c2}X) = (1.80^{+0.23}_{-0.28}) \times 10^{-3}$. These numbers are summarized in Table I.

Some of the $B \to \chi_c$ decays result from "feed down" from the $\psi(2S)$; these are not forbidden by factorization. In order to determine the rate for direct decays to the χ_c states, the $\psi(2S)$ contribution must be subtracted. This feed down is estimated using the Particle Data Group $B \to \psi(2S)X$ and $\psi(2S) \to \chi_c\gamma$ branching fractions. After correcting for feed down we find: $\mathcal{B}(B \to \chi_{c1}X) = (3.32 \pm 0.22) \times 10^{-3}$, and $\mathcal{B}(B \to \chi_{c2}X) = (1.53^{+0.23}_{-0.28}) \times 10^{-3}$.

Significant sources of systematic error are in the efficiencies for lepton identification (2% per lepton track), tracking (2% per track), photon detection (2%), as well as daughter branching fractions (6% for χ_{c1}, 8% for χ_{c2}), and fitting systematics (4% for χ_{c1}, 10% for χ_{c2}). The systematic errors are summarized in Table II.

The fit for the χ_{c1} and χ_{c2} yields is sensitive to the signal and background shapes. We estimate the error associated with the fit by performing the fit in a variety of ways including: fixing the signal means, widths, and tail shapes to Monte Carlo values (with the widths multiplied by a scaling factor and separately by adding a random number from a Gaussian distribution generated to yield the desired width increase); allowing the means to float, with the widths and tail shape fixed; allowing the means and widths to float, with the tail shape fixed; and allowing all parameters to float. In all cases, when a parameter is allowed to float, the χ_{c1} and χ_{c2} line shapes are constrained appropriately as with the standard fit. Two methods of fitting the backgrounds are also used: fixing the background with the sidebands (as with the standard fit) and allowing the background shape to float freely. The one combination that is not used is to fit with a free tail shape and a free background shape as there can be a trade off between the background area and tail area in the fit.

In addition to the above fits, we confirmed that a third-order polynomial is sufficient to fit the background by performing a fit to the background Monte Carlo; adding additional terms did not improve the confidence levels of the fits. The fitting systematic error is assigned from the largest variation between the fits described above and our standard fit.

The χ_c momentum spectra are interesting as they can give clues to the production mechanisms. The high momentum end is dominated by two-body decays to $\chi_{c1}(\chi_{c2})K$ and $\chi_{c1}(\chi_{c2})K^*$ while the low end may be from higher mass K^* resonances, multi-body decays or feed down from $\psi(2S)$. To determine the momentum spectra, we divide the data into sets based on the momentum of the χ_c candidate. We then fit each distribution for the χ_{c1} and χ_{c2} yields, which are converted into differential branching fractions, corrected bin-by-bin for the detector efficiency. The resulting momentum spectra, shown in Fig. 2, are broad indicating that a large component of either multi-body decays or higher K^* resonances is present. The shaded histogram in Fig. 2 shows the χ_{c2} momentum distribution for Monte Carlo-simulated $B \to \chi_{c2}K$ decays, which indicates that almost all χ_{c2}'s from these decays have momenta between 1.2 and 1.6 GeV/c. After doing a fit of this Monte Carlo histogram to the data histogram we find an upper limit at the 90% confidence level of 5.0×10^{-4} for the $B \to \chi_{c2}K$ branching fraction. The shaded area in Fig. 2 corresponds to this upper limit. A more detailed analysis of this decay is forthcoming.

In summary, we report the first statistically significant observation of χ_{c2} production in B-meson decays. The $B \to \chi_{c1}X$ and $B \to \chi_{c2}X$ branching fractions are measured to be $(3.63 \pm 0.22 \pm 0.34) \times 10^{-3}$ and $(1.80^{+0.23}_{-0.28} \pm 0.26) \times 10^{-3}$, respectively, where the first error is statistical and the second systematic. After subtraction for feed down from $\psi(2S)$, we find the direct branching fractions to be $(3.32 \pm 0.22 \pm 0.34) \times 10^{-3}$ and

TABLE I: Yields and branching fractions. Errors are statistical only.

| | χ_{c1} | | χ_{c2} | |
	Yield	BF (10^{-3})	Yield	BF (10^{-3})
Fit	2529 ± 127	—	611 ± 76	—
Continuum subtracted	2391 ± 142	3.63 ± 0.22	607^{+76}_{-94}	$1.80^{+0.23}_{-0.28}$
Feed down subtracted	—	3.32 ± 0.22	—	$1.53^{+0.23}_{-0.28}$

TABLE II: Systematic Errors.

	χ_{c1}	χ_{c2}
Lepton identification	4%	4%
Tracking efficiency	4%	4%
Photon efficiency	2%	2%
$\mathcal{B}(\chi_c)$	6%	8%
Monte Carlo Statistics	1%	3%
Fit	4%	10%
Total	9%	14%
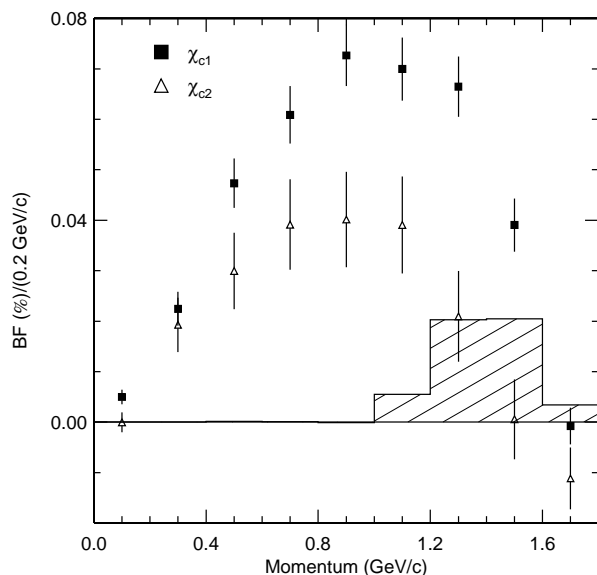
FIG. 2: Branching fractions for $B \to \chi_{c1}X$ and $B \to \chi_{c2}X$ as a function of χ_c momentum in the e^+e^- center-of-mass frame. Background from continuum processes and feed down from $\psi(2S)$ have not been subtracted. The shaded region has the expected shape for a contribution from $B \to \chi_{c2}K$.

$(1.53^{+0.23}_{-0.28} \pm 0.27) \times 10^{-3}$ respectively. The non-zero χ_{c2} production is an indication that the factorization model does not give a complete picture for charmonium production in B-meson decays. The momentum spectra include a large low momentum component, indicating either multibody final states or final states with higher resonant K^* production.

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